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The Radar-Based Short Term Prediction
of the Time-Space Evolution of Rain Fields

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A new method is developed in order to track and predict in short term (15 min - 1 hr lead times) the spatial configurations, the velocity vectors and the rain intensity textures of the potentially flood producing rain fields that are detected on a radar scope. First, the rain field is decomposed into simple, tractable elements. Then a statistical adaptive forecasting scheme is developed in order to predict the evolution of each of these elements in time and space. The composition of these elements forms the complete rain field with respect to its spatial configuration, location and rain intensity texture at each prediction lead time. The method is currently being applied to the radar data of rain fields. Some application results are given.

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TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

I.1. OBJECTIVE

The overall objective of this project is to develop a radar-based statistical scheme for the short-term prediction of the evolution of rain fields in time and space. This objective is accomplished by developing a new statistical procedure in order to extrapolate in time and space the spatial configurations, the velocity vectors and the rain intensity textures of the rain fields that are detected on a radar scope, in 5 to 15 minute time intervals for a maximum length of one hour over spatial scales of several kilometers. Here, the term "rain intensity texture" shall mean the spatial variation of rain intensity over a rain field echo.

I.2. BACKGROUND INFORMATION AND RELATED ONGOING RESEARCH

The "short-term prediction" of the rain fields will mean tracking the time-space behavior of these fields at time increments of 5 to 15 minutes and forecasting the future time-space behavior of these fields for the lead times in the range from 5 minutes to at most one hour at each forecasting stage.

A radar-based short-term rain field prediction scheme which can detect a rain field several hours in advance of its arrival onto a geographical region of interest and which can then extrapolate the spatial configuration, the rain intensity texture and the complex motion of this field in time and space onto the region several hours ahead of its actual arrival is yet nonexistent at real time operational level over the U.S.A. However, countries like Canada, England and Japan have already developed such schemes for the short-term forecasting of rain fields (Browning, 1982).

The Canadian short-term prediction scheme, developed by Bellon and Austin (1976), is called the Short-Term Automated Radar Prediction (SHARP) method. This method utilizes simple cross-correlation analysis of the entire radar-observed rain field to determine the average translation of the field with time. Hence, the method results in one translation and forecast error for the entire rain field. As such, this method is useful for those storms where the organization of rain areas at microscale and small mesoscale within the rain field are not pronounced. However, in the case of severe convective storms such as multicell storms and squall lines there is a very pronounced rain intensity variation within the rain field due to the concentration of high rain intensity rates at the microscale convective cells. Therefore, the SHARP method is not suitable for the short-term prediction of severe convective rain storms.

The English short-term prediction scheme, as described by Conway and Browning (1988), is basically a rain field centroid tracking method. In this method the radar-observed rain field data are preprocessed using a low threshold to classify areas as containing rain or no rain. Adjacent grids of rain are combined into clusters. The centers of mass of the clusters are determined without regard to actual precipitation intensity, thus areal centers of mass are determined. These centers are then extrapolated individually. This method is superior to SHARP within the context of convective rain field prediction since it is possible to track and extrapolate the individual clusters within a rain field by means of their centers of mass. However, this method does not account for the significant rain intensity variation within a convective rain field since it only considers rain and no-rain areas. Furthermore, the individual rain field clusters are translated with a constant motion vector and constant spatial configuration without regard to the evolution in the motion of the rain cluster and to the growth/decay of the size of the cluster.

The Japanese short-term prediction scheme (Ishizaki et al. 1989) uses mainly the echo-tracking method where the sequential rain fields, as observed on the radar screen, are correlated. Then based on these correlations, the fields are extrapolated. Also the growth and decay of the rain fields are taken into account. Ishizaki et al. (1963) report very satisfactory prediction results for one-hour-ahead lead times.

The first attempts in the development of a remote sensor based short-term prediction scheme for severe rain storms were carried out in the U.S.A. by Greene and Clark (1974). In their extrapolation scheme Greene and Clark considered only the prediction of the movement of a radar-detected rain field in time and space. They predicted the movement of the rain field through the use of motion vectors. They estimated the mean motion vectors of the rain field by a statistical binary matching procedure. The application results of Greene and Clark show that the statistical binary matching technique for the estimation of the mean vector displacement of the rain fields in time yields reasonably satisfactory results at the storm scale. However, the same application results show that the binary matching technique cannot predict the movements of the small mesoscale areas and rain cells within the rain fields. Hence, the extrapolation scheme of Greene and Clark (1974) can not predict the change of the rain intensity pattern within a rain field as the field moves from its initial position of radar detection towards the geographic region of interest. Furthermore, this extrapolation scheme can not predict the change in the spatial configuration of the rain field which is very important in deciding how the rain field covers the geographical region of interest.

More recently, Alaka et al. (1979) utilized the binary matching technique of Greene and Clark (1974) in order to calculate the displacement vector for extrapolating the rain fields. They chose the rain field displacement vector as the one which produced the largest number of matching grids between the present echo pattern and the echo pattern at the prior time point. Then they used this displacement vector in extrapolating the present rain field echo to its future position at the next time point. In addition to the above-discussed problems, encountered in utilizing the binary matching technique for calculating the rain field displacement vector, this technique considers only the most recent displacement of the field. As such, this method does not account for the historical trend in the motion evolution of the rain field. However, this trend information becomes very valuable as the extrapolation lead times get longer.

Alaka et al. (1979) also modeled the growth and decay of rain cells. They compared the current rain field echo by the most recent rain field echo after this echo was extrapolated to the "current time" position by the already determined displacement vector. The positive (negative) differences in the two consecutive echoes were then added (subtracted) to (from) the current echo in order to find the new echo at the new forecast lead time. Again, this approach considers only the most recent change in the rain field evolution and does not account for the historical trend in the rain field evolution. However, the trend information is very important for the prediction of the rain field for the longer lead times.

From the above survey it can be concluded that a short-term remote-sensor based comprehensive prediction scheme which can extrapolate in time and space the evolving spatial configuration, motion and fine intensity texture of a severe rainstorm is yet to be developed in U.S.A. This report discusses the development of such a predictive scheme.

II. THE PREDICTION METHODOLOGY

The basic components of a short-term rain field prediction scheme are (i) the detection of a rain field by a remote sensor on a fine time-space grid several hours in advance of its arrival onto a geographical region of interest, and ii) the extrapolation of the remote sensed rain field in time and space in order to predict whether and how the rain field will cover the region of interest.

Presently, the National Weather Service (NWS) uses the weather surveillance radar (WSR-57) in observing and tracking the rain fields. WSR-57 scans the rain fields azimuthally and displays their signals on a plan view, called a plan position indicator (PPI). With the WSR-57 PPI scope one can easily detect the horizontal location, areal configuration, orientation, and rain intensity distribution of rain fields which are approaching a geographical region of interest. The WSR-57 is a non-coherent type radar where "no account is taken of the phase of the returning radar wave with respect to the phase of the transmitted wave" (Battan, 1973). As such, WSR-57 can not measure the motion of a rain field directly. The motion trajectories of rain fields are observed indirectly by tracking their evolution in time, as they are observed on the WSR-57 radar PPI scope. Our study is based on WSR-57 radar observations of rain fields.

In order to predict the rain fields in time and space for short lead times it is necessary to develop a statistical scheme which can extrapolate in time and space the spatial configurations, the velocity vectors and the rain intensity textures of the rain fields that are detected on a radar scope.

The statistical binary matching technique employed by Greene and Clark in their extrapolation scheme falls within the realm of pattern recognition. The limited success of Greene and Clark is basically due to the fact that the binary matching scheme can only differentiate between two rainfall intensity levels which were taken as zero intensity and positive intensity by Greene and Clark. Therefore, it is not possible to differentiate the fine rain intensity features of the rain field, and hence, it is not possible to detect the change in the rain intensity distribution within the field as the field evolves in time. One can describe the fine rain intensity texture of a radar-detected rain field and track the change in the texture in time and space as well as the change in the spatial configuration of the rain fields by the "contours" method of pattern recognition theory (Niemann, 1981). Using this method, one describes the rain intensity maps of a rain field at a fixed time in terms of a number of rain intensity contours. Then one can track and describe the change in the spatial configuration and rain intensity distribution of the complete rain field in terms of the change in the spatial configuration and location of each individual rain intensity contour with time. Since the composition of all individual rain intensity contours comprises the complete rain field, the evolutions in individual contours, when contours are combined together to form the complete rain field, actually yield the time-space evolution in the spatial configuration and rain intensity texture of the whole rain field.

At this point a basic problem is how to describe mathematically the geometry of an individual rain intensity contour and how to describe mathematically the change in the location and spatial configuration of this contour. This problem requires a substantial amount of research. A promising solution avenue at present is the decomposition of a contour shape into some simple geometric shapes, the so called "simple constituents" of the pattern recognition theory (Niemann, 1981). These simple constituents can be a) a group of triangles which are combined together, b) a group of circles which are combined together, c) a group of ellipses which are combined together d) a group of polygons which are combined together or, e) any combination of triangles, circles, ellipses and polygons which are combined together in order to form the irregular shape of a contour. Among these alternatives, the approximation of a rain intensity contour by a combination of circles has already been investigated by Kavvas et al.,(1987). However, in this study we use polygons whose combinations yield the rain field shapes. The basic rationale for using polygons instead of other geometric shapes is that one can approximate any geometric figure to the desired fine scale by a polygon. While one needs to use many circles of varying sizes to approximate a complicated geometric figure (see Kavvas et al. (1987) for details), one can achieve a similar approximation by a polygon which shall have significantly fewer edges than the number of necessary circles. This statement holds true also when one compares polygons to other geometric shapes such as ellipses, rectangles, triangles, etc. Therefore, by utilizing a polygon to approximate the irregular shape of a rain intensity contour very significant economy in the number of parameters is achieved. Since in the computerized rain field forecasting operation fewer parameters lead to lesser computer storage requirements and faster computer processing times, it is extremely important to achieve a good representation of irregular rain intensity contours by a geometric model with as few parameters as possible. Afterall, in the operational short term prediction of severe, convective rain fields the forecaster may have only 15-30 minutes to execute the forecast and to inform the concerned parties.

Once a contour is approximated by a polygon, then its evolution in space can be tracked and described in terms of the evolution in the edges which make up the polygon and of the evolution of the centroid location of the polygon. Consequently, the prediction of the future spatial location and of the future evolution in the spatial configuration and the rain intensity texture of a rain field reduces to the prediction of the future centroid locations and future shapes of the polygons each of which make up the individual rain intensity contours. In turn, the individual rain intensity contours combine to form the complete rain field. The tracking of the centroid location of a polygon will yield the information about the evolution in the velocity vector of the rain intensity contour which this polygon represents. Finally, the velocity evolution of the individual contours, when these contours are combined together to form the rain field, will yield the necessary information about the evolution in the complicated motion of the complete rain field. In short, once a rain field is decomposed first into rain intensity contours, then decomposed further into simple constituents, the tracking and the prediction of the evolution of this rain field in time and space becomes equivalent to the tracking and the prediction of the changes in the parameters which describe these simple constituents.

The next step is the short-term adaptive statistical prediction of the change in the parameters of the polygon which we selected to make up the rain field. It may be remarked that this prediction is not only in time but also in space. Therefore, the grids employed for this prediction exercise are 3-dimensional time-space grids which preferably will have a time increment of about 5 to 15 minutes and a spatial increment of about 1 to 4 km^2 in order to detect and to predict the highly varying rain intensity structure of the rain fields.

Due to the fine time-space grid size which is necessary for the proper prediction of the rain field evolution, the statistical prediction procedure will be computation-intensive. Furthermore, very little historical data is available for the calibration of the forecasting scheme prior to the on-line, real time forecasting.

In this research effort forecasting techniques, exhibiting a range of complexity, are tested in order to find the most suitable one in terms of i) requiring the fewest computations, ii) requiring the smallest computer memory, iii) ease of calibration in the face of very limited historical data, iv) being most adaptable to the highly varying nature of the rain field evolution, and v) yielding the best forecasts in terms of the smallest forecast errors (e.g. in terms of the minimum mean-square-error).

We consider the well-documented methods of i) exponential smoothing, and ii) Kalman filtering as possible candidates for the adaptive forecasting scheme. These methods are adaptive to the changes in the forecasted parameter and, thereby, are suitable for the rapid evolution of severe convective storms.

The exponential smoothing employs a feedback concept where the new forecast is adjusted for the error committed in the previous forecast. It also allows the option for varying the relative weight given to recent versus past observations. This is particularly relevant to convective rain fields where the field evolution may demand that the history of simple constituent parameters focus primarily on recent observations. Furthermore, this method requires very little storage memory, with only the present observation and the previous forecast of the parameter required to make a new forecast.

In this study we have used exponential smoothing for the adaptive statistical prediction of the change in the parameters which describe the spatial location and shape of the polygons to make up the rain field. Some sample results of this prediction method are given below.

III. A SAMPLE OF THE PREDICTION RESULTS

In this study we are using the weather radar data of the Cincinnati Airport in U.S.A. This airport is equipped with the WSR-57 radar which takes photographs of the rain fields that are depicted on the radar PPI scope which has an effective radius of 201.13 km. The photographs of rain fields are taken at least every 5 min and as often as every 40 sec during the passage of a rain field on the radar scope. The processing of the original radar data was discussed by Kavvas and Herd (1985). In its final processed form the radar data is provided in PPI microfilms where the rain fields are represented in terms of 6 rain intensity contours. Again, Kavvas and Herd (1985) explain in detail these contours with respect to their rain intensities and to their interpretation. Since we have 12 years of voluminous radar microfilm data of the Cincinnati Airport we have concentrated our prediction studies only on those convective storms with flood producing potential during the first 20 days of April of each of the 12 years of record. In Figures 1-9 below, our prediction methodology is illustrated in terms of its application to the evolution of a rain contour (with a second-intensity level range of 0.508-2.79 cm/h) which represents a raincore that was detected on the radar scope in April 5, 1982 during 18:36-23:56 GMT. In each Figure we give a) the current (present) location and spatial configuration of the rain contour, b) the forecasted location and spatial configuration of the rain contour for a 30 min lead time and c) the observed location and spatial configuration of the rain contour for the 30 min lead time as the field evolved on the radar scope. The centroid locations are shown by the strings of connected dots in Figures 1-9. The string of dots which starts on the left hand side and ends in the right hand side when compared to the other string, is the trajectory of observed rain field centroid locations. The other string denotes the trajectory of predicted rain field centroid locations. From these figures one can note the observed and the forecasted contour centroids at 15 min time increments. For the initial 30 min lead time, there is no information about the motion and shape of the rain contour at the time of its first appearance on the radar. Thus, we have based this initial forecast on the statistical information which we have obtained by the analysis of the historical rain field data, obtained by the weather radar. This initial forecast, which is made at the current time of 5 min after the appearance of rain contour on radar screen, is shown in Fig. 1. The subsequent 30 min lead-time forecasts at every 15 min increment are shown in Figures 2-9. As seen from these figures, our forecasting methodology can adapt to the rapid changes in the motion direction and in the shape of a rain intensity contour which is very typical of the severe convective rainstorms observed over the Midwestern U.S.A. which our weather radar partly covers.

IV. DISCUSSION AND FINAL REMARKS

We have presented in this report the preliminary results of a new method for the short-term prediction of rain fields. The method, as reported here, is only applicable to the tracking and prediction of individual rain regions, where these regions may be individual rainbands, individual raincores or individual raincells.

This report explains the first year accomplishments of a research project which was jointly supported by the U.S. Air Force and U.S. Geological Survey. The continuing research, being funded by USGS is already achieving significant advances over the first-year accomplishments. The most significant advance being the unification of the tracking and forecasting of individual rain field elements in order to forecast any complex rain field shape and intensity texture. Currently, we are applying our most recent findings to the prediction of complex rain field evolutions. We are also planning to incorporate Kalman filtering into our prediction methodology and compare its performance against that of our current exponential smoothing method described in the report.

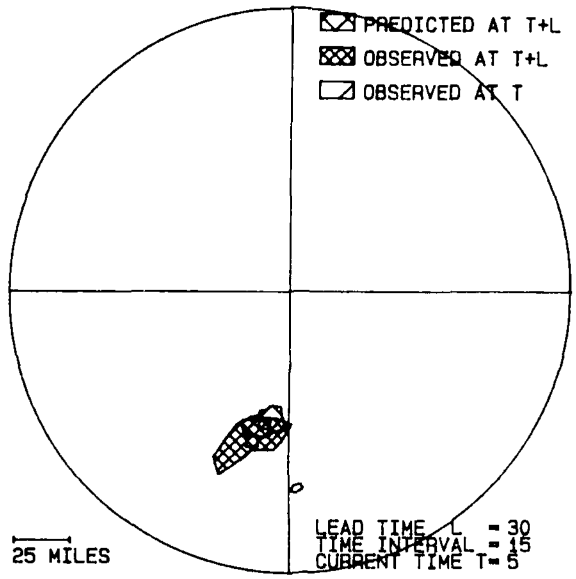

Fig. 1 30 min lead time forecast of a rain field from the current time of 5 min.

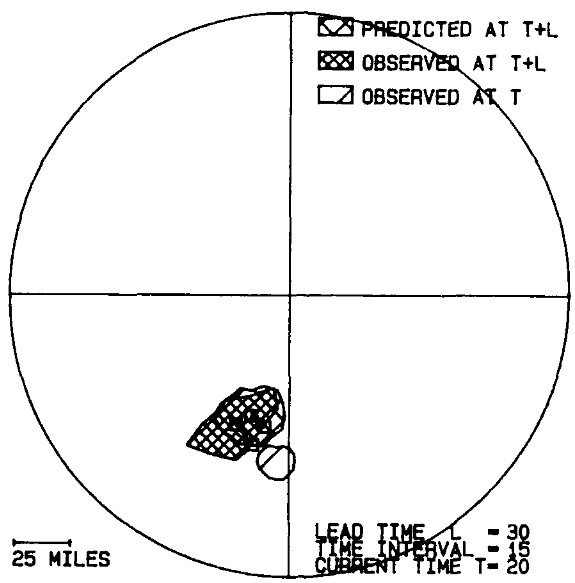

Fig. 2 30 min lead time forecast of a rain field from the current time of 20 min.

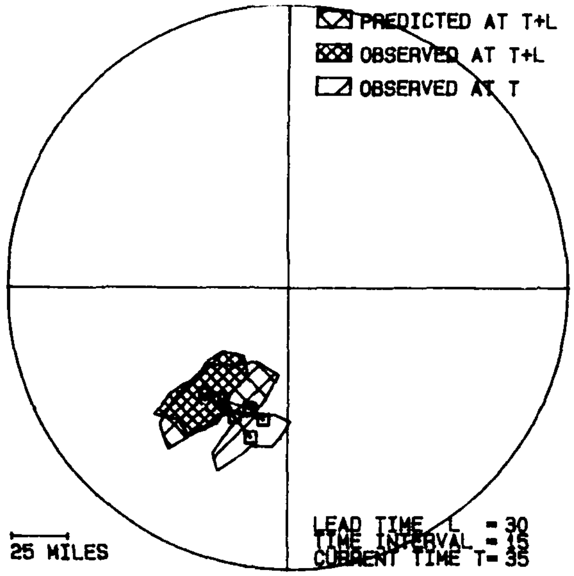

Fig. 3 30 min lead time forecast of a rain field from the current time of 35 min.

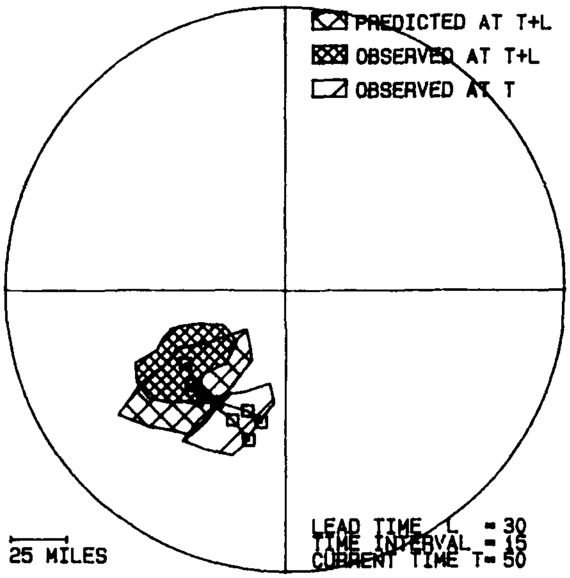

Fig. 4 30 min lead time forecast of a rain field from the current time of 50 min.

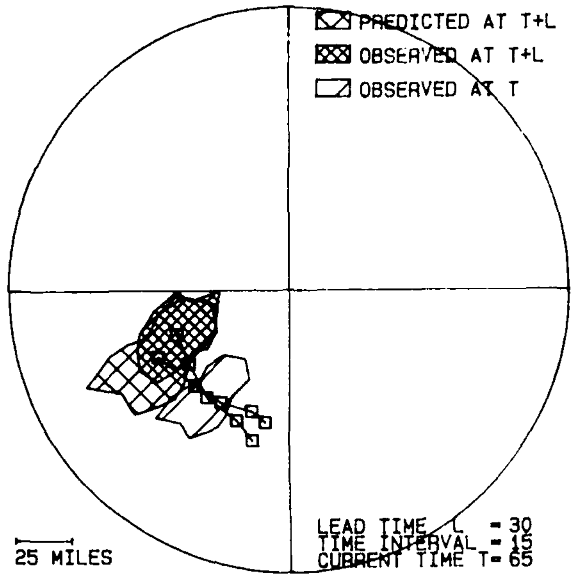

Fig. 5 30 min lead time forecast of a rain field from the current time of 65 min.

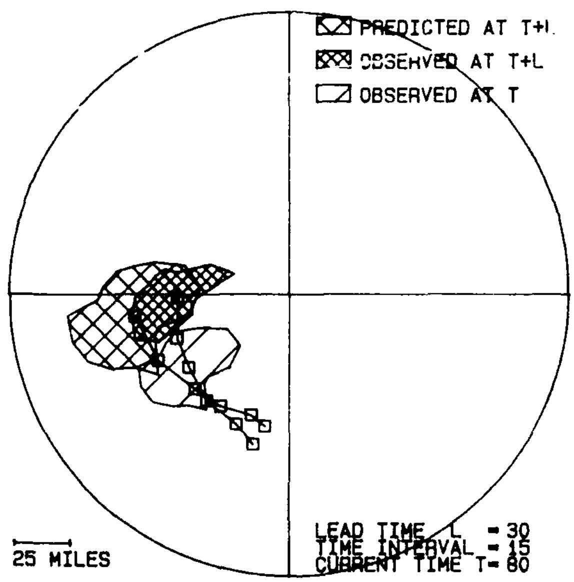

Fig. 6 30 min lead time forecast of a rain field from the current time of 80 min.

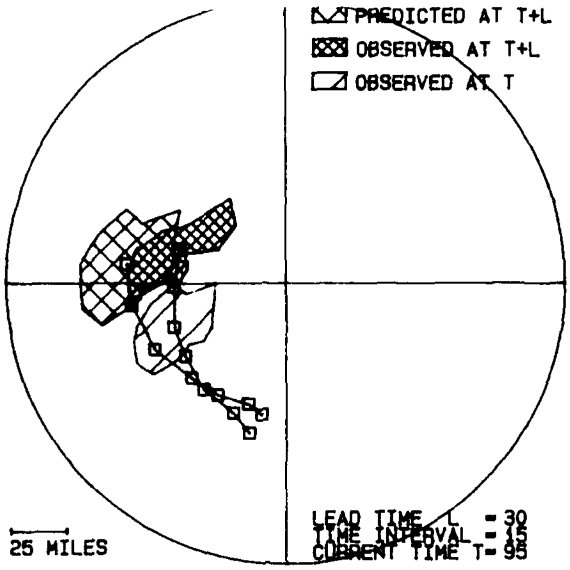

Fig. 7 30 min lead time forecast of a rain field from the current time of 95 min.

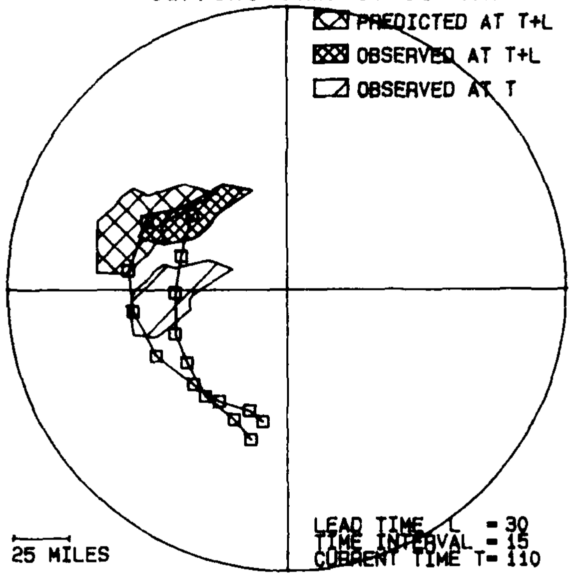

Fig. 8 30 min lead time forecast of a rain field from the current time of 110 min.

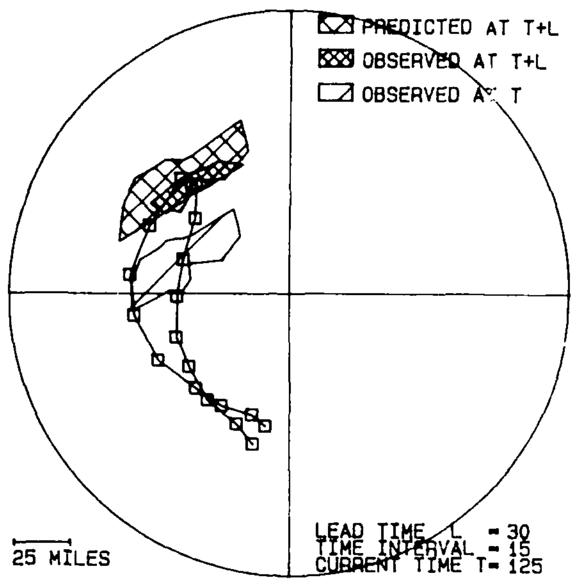

Fig. 9 30 min lead time forecast of a rain field from the current time of 125 min.

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